Cyclic relationship between saturation and tensile strength in the near-surface zone of infrastructure embankments

R.A. Stirling, P.N. Hughes, C.T. Davie & S. Glendinning
Newcastle University, Newcastle-upon-Tyne, UK

ABSTRACT: The near surface properties of engineered fill have a significant impact on its engineering behaviour. A common way in which soil will change is through cracking due to the effects of desiccation, vegetation and climate. This has an impact on soil mass permeability, strength and stiffness and hence slope failure susceptibility. Knowledge of the tensile strength and degree of saturation relationship is essential to understand the development of desiccation cracking. This paper presents a study to establish the cyclic relationship between tensile strength and soil water content in a re-moulded glacial till. Testing was conducted using a direct tensile strength test modification to standard direct shear apparatus. As with the soil-water retention, the relationship between soil water content and tensile strength shows hysteretic characteristics. Furthermore, this relationship was found to develop upon repeated drying and re-wetting cycles. This has implications for the degradation of near surface material on engineered infrastructure slopes.

1 INTRODUCTION

Knowledge of the tensile strength properties of geomaterials is important in a number of engineering applications. Engineered fills in embankments, cuttings and dams, landfill liners and other earth structures are susceptible to tensile failure, particularly in the near surface "vadose" zone where evapotranspiration and seasonal wetting and drying can induce shrink-swell cyclicity.

Much work has been conducted into the generation of tensile stresses due to restrained shrinkage relatively recently including the following principle contributors, Kodikara et al. (2004), Hu et al. (2006) and Peron et al. (2009). The development of tensile stress is generally accepted as arising from non-uniform drying or any frictional boundary effect up to a magnitude that may exceed the tensile strength of cohesive soils leading to what is increasingly understood to be a dominant criterion for the initiation and propagation of desiccation cracking (Peron, et al., 2009). Therefore the capacity to characterise the tensile strength/stiffness behaviour of geomaterials is of importance.

There exist a number of tensile tests available for the characterisation of geomaterials. These can be separated into two categories, direct and indirect tests. Direct tests include modification of triaxial testing apparatus (Tang and Graham, 2000; Heibrock et al., 2003; Witt and Zeh, 2007) and modification of direct shear testing apparatus (Nahlawi et al., 2004; Tamrakar et al., 2005; Trabelsi et al., 2012). Indirect tests include the Brazilian tensile test (Frydman, 1964; Krishnayya and Eisenstein, 1974) & Hollow Cylinder Triaixial test (Alsayed, 2002). Each of these approaches have their advantages and limitations although direct testing is generally preferred as requiring relatively simple sample preparation and testing procedures making this class of test both effective and economical. However, serious consideration must be given to the potential for squeezing of low stiffness material by shear keys and loading jaws leading to uneven stress distributions and hence inaccurate stress measurement.

In this work, a direct tensile strength test has been used to investigate the effect of drying-wetting cycles on the development of the tensile strength – water content relationship. This has been conducted in the context of observed degradation of compacted engineered fill at the near surface of infrastructure embankment structures.

2 TESTING METHOD

2.1 *Equipment*

An adaptation of existing direct shear apparatus was developed in order to test direct tensile behaviour. The test rig chosen for modification was a conventional 100 mm x 100 mm Wykeham Farrence direct shear test rig. The modifications to the rig consisted of two PVC loading jaws that when combined form a sample aperture in the shape of two mirrored isosceles trapeziums, commonly referred to as a 'bow-tie'. These jaws can be inserted into the carriage where the shear box is usually placed. A schematic of the loading jaws is presented in Figure 1a, how this device then fits into a conventional direct shear rig is shown in Figure 1b. The advantage of this system is that the loading jaws can be quickly removed allowing the rig to be returned to its original purpose as the need arises.

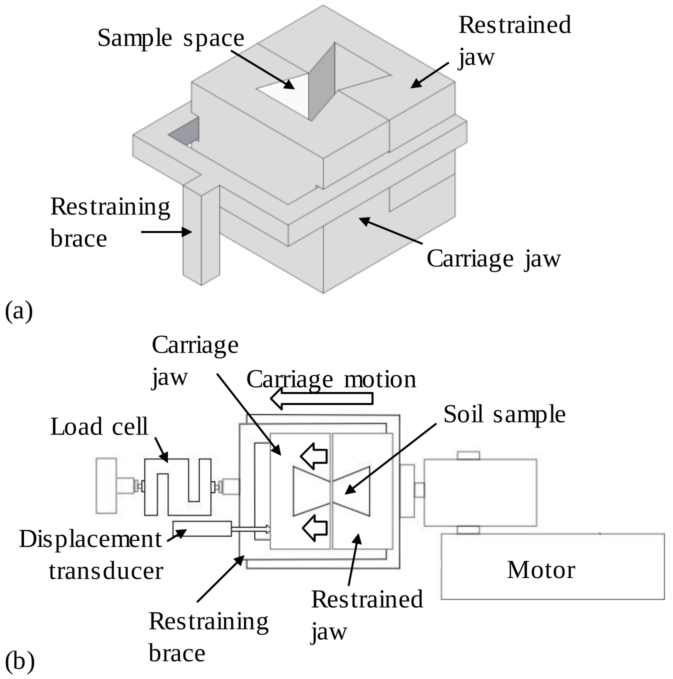

Figure 1. Tensile test apparatus comprising (a) loading jaws and (b) schematic of testing rig.

2.2 *Material*

The material investigated was an engineered fill comprising glacial till representative of embankments in the north of the UK. Such soils are prone to shrink-swell behaviour which contributes to the progressive failure of infrastructure embankments as well as desiccation cracking phenomena.

The Atterberg limits, tested in accordance with BS 1377 (1990), were 43% and 21% for Liquid and Plastic Limits respectively which classifies the material as intermediate plasticity. Compaction characterisation was conducted to BS 1377 (1990) using normal Proctor (light) compaction which found the maximum dry density to be 1.71 Mg/m^3 at a 15% optimum water content. Lastly, the particle distribution of the material was established and is provided in Figure 2 where the soil is shown to be relatively well-graded in the portion >2μm.

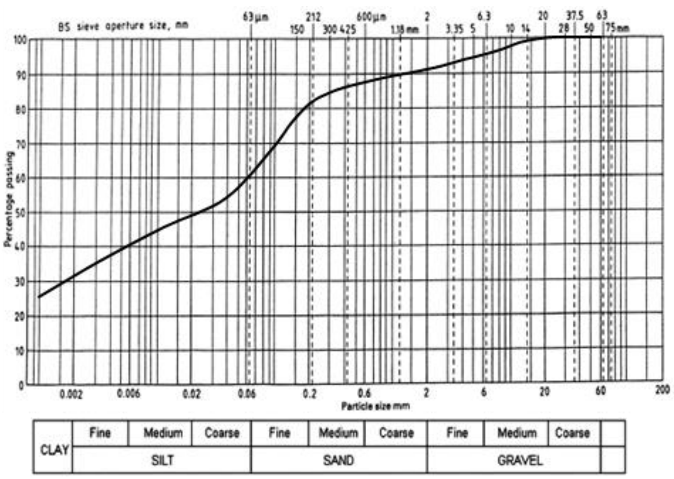

Figure 2. Engineered fill particle size distribution.

2.3 *Sample preparation*

The above fill material was prepared by air drying to residual moisture content before being passed through a 5 mm sieve. This process is known to alter the natural PSD of the natural material; however, it was deemed impractical to test soils whereby individual grains constituted greater than 2% of the total volume of the sample (78.3 ml).

Following drying, water was then added to bring the soil in a mechanical mixer to a predetermined water content (23%) and the bulk sample was then wrapped in two layers of uPVC film and left to equilibrate for at least 24 hours. After this period, a sub-sample of soil was weighed such that when a sample is produced using a bespoke steel press, a desired average dry density (1.65 Mg/m^3) was achieved. This process allowed the rapid production of samples with consistent water contents, densities and dimensions.

Samples were subsequently air dried again until the desired water content was reached. On reaching the required water content, samples were then resealed for 24 hours to ensure an even re-distribution of water within the specimen prior to testing. Where samples were required to be tested along the wetting path, samples were first allowed to dry to their residual value (where no mass change was observed). A humidity chamber was then employed in order to gradually increase these samples' water content. The insulated chamber measured approximately 450 mm x 300 mm x 300 mm and contained a 20-30mm water bath within which was placed up to 3 ultrasonic water foggers. This maintained a high relative humidity enabling the samples to absorb moisture gradually as a more rapid approach would inevitably lead to destruction of the soil fabric and likely sample disintegration. For a typical dried sample to be returned to a water content of 20%, a period of approximately 7 days was required.

2.4 *Testing procedure*

Specimens are placed in the loading jaws and a constant motor speed selected. The carriage is then propelled leading to separation of the loading jaws. The resultant load is transmitted through the sample and recorded continually until the two halves of the sample are completely separated and the load reading returned to a residual value. It may be noted that non-zero stress values are recorded post specimen failure indicating, as in any mechanical system, a level of internal system friction/inefficiency.

A range of displacement rates are available by using an existing direct shear rig. However, a motor rate of 0.61 mm/min was used. Due to the stiffness of some samples, the true displacement rate has been found to deviate from the applied rate. Hence, true displacement was measured directly as the carriage jaw was displaced.

3 RESULTS

3.1 *Tensile stress-strain behaviour*

The tensile stress-strain data gained from testing the clay fill along the initial drying path are presented in Figure 3. At the start of each test, a period of sample seating may be seen in the form of low sustained stresses with developing strain. It can be seen that samples tested at moisture contents below 15% show a somewhat linear stiffness with slight stiffening prior to the ultimate strength being reached. At the ultimate strength, samples were found to fail with an instantaneous fracture across the neck of the sample. Subsequently, stress is shown to drop sharply; however, in the wetter sample at 22% (approx. plastic limit) a strain softening behaviour is apparent post-failure at a substantially lower ultimate strength. This is shown by the gradual decrease in stress upon returning to the residual value with continued straining. These samples exhibit a less well defined brittle fracture and eventually divide following a period of neck thinning in a ductile manner.

3.2 *Drying-wetting-drying path*

The testing program was conducted with the ultimate aim of investigating the tensile strength change with cyclic drying and re-wetting of clay embankment fill. To this end, the following data is presented showing this relationship along an initial drying, wetting and subsequent re-drying path (Figure 4).

The initial drying path shows a typical trend of exponentially increasing tensile strength with decreasing water content. This data has been curve fitted with an R^2 value of 0.84, the highest fit of all the strength-water content data. Upon wetting, a similarly exponential trend may be fitted. However, the wetting relationship follows much lower strength values and at water contents >20%, negligible tensile stress is maintained. The second drying path exhibits higher tensile strengths than that of the wetting trend yet is considerably weaker than the initial drying curve.

4 DISCUSSION

Tensile strength is increasingly understood to be a crucial parameter in the study of desiccation crack initiation and stable crack propagation in cohesive soils. Traditionally, the relationship between tensile strength and water content established along an initial drying path has been considered as a main influence on the temporal and spatial distribution of crack initiation during progressive soil drying. However, this relationship has been found to undergo translation toward the origin of both σ_t and ω axes upon cyclic wetting and drying.

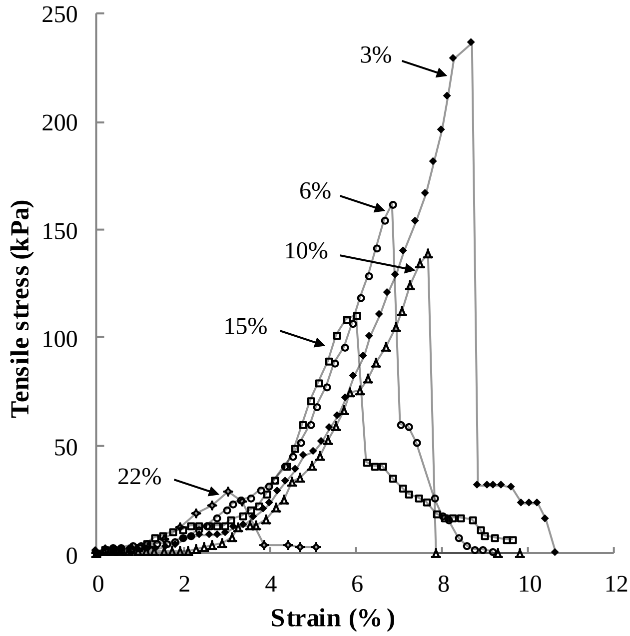

Figure 3. Typical tensile stress-strain relationship at various water contents.

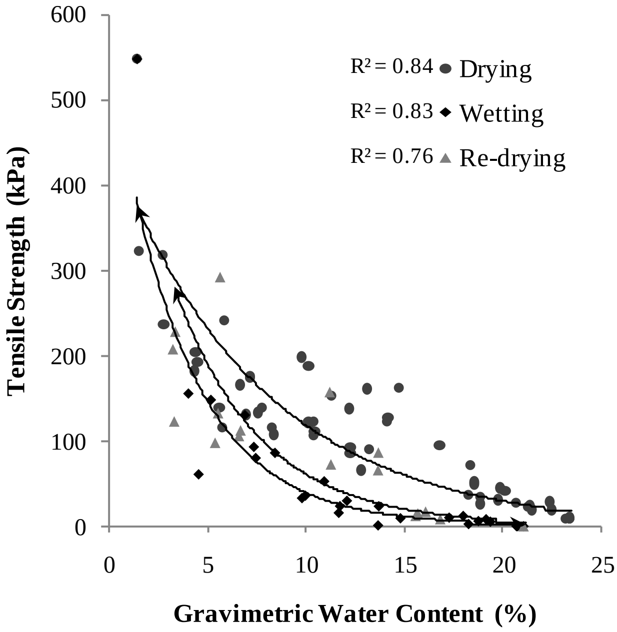

Figure 4. Tensile strength relationship upon initial drying, wetting and re-drying.

The development of tensile strength in clay soils with changing water content is understood to be related to (but not solely a result of) an inherent change in matric suction. In granular soils, suction is the governing mechanism behind resistance to tensile stresses, in compacted clay fills soil fabric is considered to play a significant role.

Crack initiation is assumed to occur by induced tensile stress brought about by restrained shrinkage due to surface desiccation exceeding the soil tensile strength under a given condition. A cracking analysis on this basis would indicate that crack initiation would occur at a given tensile strength which exists at specific water content. The following discussion precedes under the supposition that cracking may or may not have occurred in the initial drying of the subject soil. Should the cracking condition have been met under initial drying then sufficient stress 'relaxation' behavior may well take place whereby subsequent generation of tensile stress may not exceed critical tensile strength and no further cracking can proceed. Notwithstanding, the use of a single, initial drying relationship is understood to result in an underestimation in the later development of crack networks.

By investigating the cyclic tensile strength-water content relationship, deterioration in the clay is evident. Hysteretic phenomena are familiar in the study of soil wetting. In the context of soil-water retention, upon wetting, lower suction is developed at a given water content than would be generated upon drying. This effect may well contribute to explaining the reduced strength shown along the wetting path. However, it is believed that deterioration of the soil fabric is the primary means of strength reduction. The development of micro-flaws during the initial desiccation stage has led to an increment of non-recoverable destruction in the structure of the compacted clay fabric. The second drying stage illustrates this loss in soil integrity. Tensile strengths are higher on drying than wetting once again though are considerably lower than on the initial drying path. The return of the curve to higher strength values on drying indicates the influence of hysteretic soil-water-air phenomena. The large contrast between the two drying paths signifies a more fundamental deterioration.

On establishing lower tensile strengths as a result of cyclic wetting and drying, the criterion by which crack initiation is believed to occur is met by the generation of lower tensile stresses. This would lead to an increased occurrence of cracking (e.g. development of an inter-connected network) with progressive drying-wetting cycles. The authors anticipate a residual tensile strength – water content relationship after repetition of drying and wetting whether this be partial or complete in either direction. As previously described, some hysteretic influence is believed to remain.

5 CONCLUSION

By developing an approach to measure the tensile strength of a typical, compacted clay embankment fill at a variety of water contents, the development of this relationship upon cycles of drying and wetting has been identified. The implication of this work is a better understanding of the tensile strength deterioration process with repeated wetting and drying in clay fills and specifically how this influences the initiation of tensile failure at the near-surface.

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